SIMPLE DRIVERS OF SNOW INSTABILITY

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ABSTRACT: Snow layers form during and after accumulation due to the interaction of meteorological and physical processes. It is known that the vertical structure and also the lateral continuity of layers depend on these processes and the boundaries set by the terrain. This study addresses the amount of variation seen among vertical profiles on slopes and within a basin. In the past years a unique dataset was acquired with more than a thousand snow micro-penetration resistance measurements covering a variety of dry-snow conditions. With recent advances in signal processing all snow layer properties relevant to slab avalanche release are extracted from a SMP signal so that the propensity to failure initiation and crack propagation can be calculated. The modelled values correspond well with field test results obtained during the measurement campaigns and the verified, local danger. We then analyzed whether the spatial characteristics found were related to simple drivers such as slope aspect, snow depth and slope angle. In general, the older the slabs the more drivers were identified. Slope aspect was certainly a prominent driver, but also snow depth influenced the distribution of snow instability. However, the direction of influence depended on the size of the dataset, probably on whether the same or different slab-weak layer combinations were present. Our findings suggest that even though spatial variations of snow instability are hard to predict, simple drivers exist that may well help to reduce the uncertainty in avalanche hazard evaluation.

KEYWORDS: snow properties, snow instability, spatial variability.

1. INTRODUCTION

Classical snow instability observations require an in depth knowledge on site selection, snow profiling and above all interpretation. As we often already know the general avalanche conditions within a region, but are interested in differences, we may look at the drivers responsible for stability patterns. Exploiting simple drivers such as terrain parameters or snow depth for snow instability estimation may be useful when making decisions in the field or interpolating snow instability information. Above all simple drivers have the great advantage that they are readily and widely available.

Various studies have investigated the relationship between snow instability and slope aspect, snow depth and slope angle. At the slope scale, Campbell and Jamieson (2007) performed rutschblock (RB) tests on slopes with large variations in aspect, snow depth and slope angle. Their results were mostly inconclusive, as on most slopes they could not find a clear relation between RB score and snow depth, aspect or slope. Furthermore, when correlations were present, they were either positive or negative.

At the basin scale, however, some studies identified correlations between specific snow properties related to snow instability and simple terrain parameters. For instance, Borish et al. (2012) and Feick et al. (2007) identified a correlation between surface hoar crystal size and elevation, which both attributed to local wind regimes. Schweizer and Kronholm (2007), on the other hand, found aspect and slope angle to be more indicative for the presence of surface hoar at the regional scale. Slope angle and aspect were also rated as important drivers of surface hoar formation and persistence by Helbig and van Herwijnen (2012) who modeled surface hoar sizes in complex terrain based on simple terrain characteristics. Schweizer et al. (2003) had analyzed snow instability observations from five periods during a winter season covering a mountain region. Among the simple drivers specified above they found that snow depth was the best indicator of snow instability. Assessing the predictive power of meteorological and snowpack properties, Zeidler and Jamieson (2004) also found snow depth to be a significant driver for instability described as the skier stability index. The above mentioned studies were mainly based on extensive manual field observations and measurements, which are extremely time consuming and observer dependent and often only provide an

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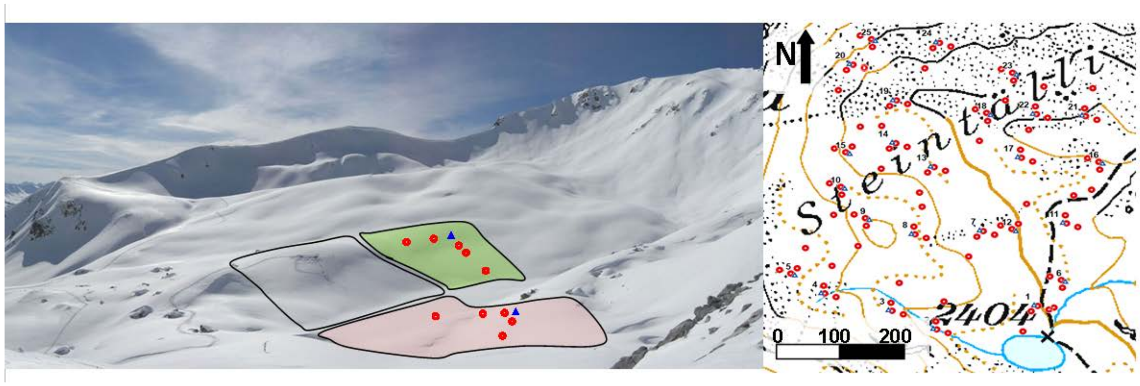

Figure 1: On the left, photography of the Steintälli field site with three out of 25 cells, one with field staff at work (#16) and two (#17 and #21) with sampling locations (red and green). On the right, map showing the field site with all cells and sampling locations. Locations indicated by blue triangles include GPS measurements, SMP and manual profiles. At other locations, indicated by red dots, SMP profiles and measurements of terrain parameters and snow depth were performed.

indirect measure of snow instability. The snow micro-penetrometer (SMP)(Schneebeli et al., 1999) on the other hand, offers a way to measure snow mechanical properties relevant for slab avalanche release objectively (Reuter et al., 2013) and at high spatial resolution. A novel approach to determine the propensity of failure initiation and crack propagation allows evaluating field measurements of snow stratigraphy in view of snow instability.

Our aim is to explore the relationships between variations of snow instability and simple drivers such as slope aspect, snow depth and slope angle at the basin scale.

2. METHODS

In the following we describe our field data set, the processing of SMP signals including the derivation of snow instability and the multiple regression analysis of simple drivers.

2.1 Field data

In the winter seasons between 2010-2011 and 2012-2013 we carried out five field campaigns at the Steintälli field site above Davos (Switzerland) under different stability conditions. The field site is close to a ski area ensuring good accessibility. Due to the absence of popular off-piste terrain and the large size of the basin, we could perform repeated campaigns without hitting old tracks. The entire sampling area spans about 400 by 400 meters and was divided into 25 cells (Figure 1). We recorded snow depth, slope angle and aspect at every SMP measurement location. Also GPS coordinates were recorded at the corner points shown in Figure 1. Nine manual snow profiles included snow grain type and size and hand hardness index. The profiles were complemented by stability tests and provide a valuable benchmark for snow instability. Stability tests include propagation saw tests (Gauthier et al., 2008) and extended column tests (Simenhois and Birkeland, 2006).

Table 1: Overview showing the number of SMP field measurements, the verified danger level and the days since the last snowfall for the field campaigns.

Date	# SMP	Danger level	Days since snowfall
28 January 2011	125	1	2 d
3 March 2011	110	3	4 d
13 February 2012	119	2	19 d
9 March 2012	102	2	1 d
10 January 2013	157	2	3 d

2.2 SMP signal analysis

In order to derive snow mechanical properties from SMP penetration resistance profiles, the signal was processed to obtain the characteristic set of microstructural parameters, namely rupture force, deflection at rupture and structural element length (Löwe and van Herwijnen, 2012). The SMP signal was then divided into layers, several slab layers, a weak layer and a basal layer, by comparing the SMP signal to the manual snow profiles with a particular focus on the most critical weakness found in stability tests. Snow density ρ

(Proksch et al., 2014), weak layer fracture energy w_f (Reuter et al., 2013), effective modulus E and strength σ (Schneebeli and Johnson, 1998) were then determined for every layer based on the micro-structural parameters. Thus, at every SMP measurement location, snow stratigraphy was characterized by the relevant mechanical properties: ρ and E for the slab layers, w_f and σ_{WL} for the weak layer, and ρ and E for the basal layers.

2.3 *Failure initiation criterion*

A criterion *S* describing the likelihood of initiating a failure at the depth of the weak layer was defined as:

$$S = \frac{\sigma_{WL}}{\tau},$$

with σ_{WL} the strength of the weak layer and τ the additional shear stress due to skier loading on top of the snowpack. The additional shear stress was modeled by a finite element simulation following Habermann et al. (2008). The additional shear stress τ exerted on the weak layer was approximated by the maximum shear stress found in the weak layer nodal elements. SMP derived values of strength are larger by about two orders of magnitude than values of shear strength found in literature (Marshall and Johnson, 2009). Hence, values of *S* are higher than found in literature.

2.4 *Crack propagation propensity*

The snowpack's propensity to support crack propagation in a weak layer may be estimated as the critical crack length r_c for unstable crack propagation. The critical crack length is obtained by finding the real, positive root of the formulation of the specific fracture energy given by Eq. 4 in Schweizer et al. (2011). This approach requires an assumption about the stiffness of the entire slab. We used the bulk effective modulus obtained from finite element simulations to account for snow stratigraphy, as assuming a uniform slab results in inaccurate estimates of the mechanical deformation energy (Schweizer et al., 2011).

2.5 *Relating snow instability to simple drivers*

Slope angle, aspect, elevation and snow depth are widely assumed to be related to snow instability. We therefore investigated if slope angle, aspect and snow depth, measured manually at every SMP measurement location in the field, related to *S* and r_c. Using stepwise multiple regressions, the predictive power of simple drivers was assessed. For this analysis a regression model is created by stepwise increasing the number of predictors until the predictive power does not improve significantly any more resulting in a final model (F-Test, significance level *p*=0.05). We report the p-values for testing if a coefficient is not zero. Only drivers with *p*-values <0.05 appear in the final model and their p-values refer to the final model. For excluded predictors the p-value is reported that would result if the predictor would be included in the final model.

Moreover, to explore the relationship between snow depth and the critical crack length, the Pearson correlation coefficient *r* and the value of significance *p* of the regression slope are presented assuming significance for $p<0.05$.

3. RESULTS AND DISCUSSION

3.1 *General avalanche conditions*

Three out of five field campaigns were carried out on days with avalanche danger 2 (Table 1). Overall, the modeled critical crack length was lowest for days with verified danger level 3 (Figure 2). Interestingly, modeled r_c values were also low on 28 January 2011, when the avalanche danger was rated as "low". The weak layer was, however, buried under a very shallow and soft slab, while our crack propagation tests gave mainly positive results: PST 46/120cm END on an east-facing slope, ECT 11/11 on a south-facing slope and ECT 23/pp on a north-facing slope. But due to the

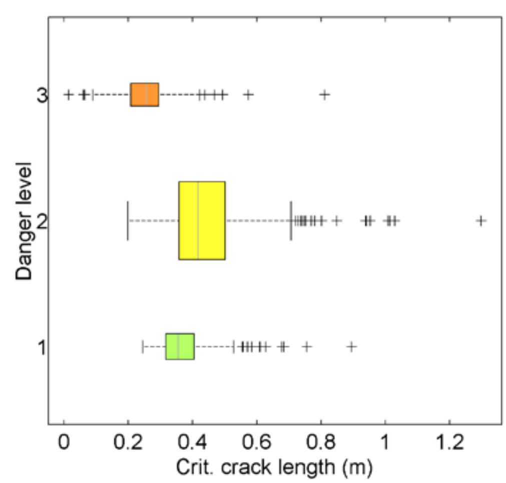

Figure 2: Modeled critical crack length by verified avalanche danger level. Width of boxes according to the number of cases (see Table 1). Whiskers extending to the most extreme data points not considered outliers (crosses) within 1.5 times the interquartile range above the 3rd and below the 1st quartile.

soft and low cohesion slab widespread crack propagation was unlikely. About one month later, on 3 March 2011, the same weak layer was buried deeper and the danger level was “considerable” which was reflected by shorter modeled crack length (orange box in Figure 2). For the danger levels “moderate” and “low”, the propensity for crack propagation was lower. Similar trends were obtained for the stability criterion *S*. However, the differences between the danger levels “moderate” and “considerable” were not as pronounced.

This result is in line with the findings of Schweizer et al. (2003), although short critical cut lengths were obtained in one situation with danger level “low”.

3.2 Simple drivers

In a next step, we investigated the predictive power of slope aspect, snow depth and slope angle for the two modeled measures of snow instability. Before we analyze the field days all together, we look at the characteristics of the single field days one by one.

General avalanche conditions

Going through the rows of Table 2 on 9 March 2012 no drivers were identified, whereas on 13 February 2012 almost all drivers were present. On 9 March 2012 the last snowfall was back one day and no driver was found among the terrain parameters or snow depth. On 13 February 2012 no new snow has been recorded since 18 days and almost all drivers were significantly related to the measured of instability. On the other field days slabs were two to four days old with one or two variables driving the distribution of snow instability. This suggests that the older the slab the better the distribution of snow instability can be described by simple drivers.

Slope aspect

The relationships were negative for all field days for the category Aspect (N-S) meaning that on slopes with aspects in the northern half-space lower values of both, critical crack length and stability criterion *S* were calculated (Table 2).

Considering all field days, the same trend towards higher propensity for crack propagation and failure initiation on slopes of generally northern aspects existed (Table 2). On slopes with aspects in the northern half-space shorter critical crack lengths were modeled more frequently than in the southern half-space (Figure 3).

Table 2: The p-values of the regression coefficients between potential drivers and the modeled critical crack length r_c as well as the stability criterion *S* shown for single field days and the entire dataset (all). Potential drivers: aspect (N-S), i.e. aspects in the northern vs. aspects in the southern half-space, snow depth and slope angle. Bold values indicating significance on a level of 5%. Black colors denoting a positive, blue colors a negative relationship.

Date	Aspect (N-S)		Snow depth		Slope angle	
	r_c	*S*	r_c	*S*	r_c	*S*
28 Jan 11	0.09	**0.01**	0.33	**0.01**	**0.01**	0.99
3 Mar 11	0.06	0.87	0.12	0.85	**0.01**	**0.01**
13 Feb 12	**0.01**	**0.01**	**0.01**	0.22	**0.01**	**0.01**
9 Mar 12	0.98	0.20	0.98	0.11	0.97	0.13
10 Jan 13	0.52	0.20	0.37	**0.01**	0.42	**0.01**
all	**0.01**	**0.01**	**0.01**	0.34	0.20	0.45

Due to the topography of our field site westerly aspects were underrepresented and we do not present a comparison of westerly with easterly aspects. The polar plot for the failure initiation criterion S looked similar (not shown).

Slope aspect was a driver not only of the crack propagation propensity but as well of the failure initiation propensity. This finding is in line with the general picture of average snow instability distributions. At the regional scale (Schweizer et al., 2003) observed that differences in snow instability were often explained by aspect.

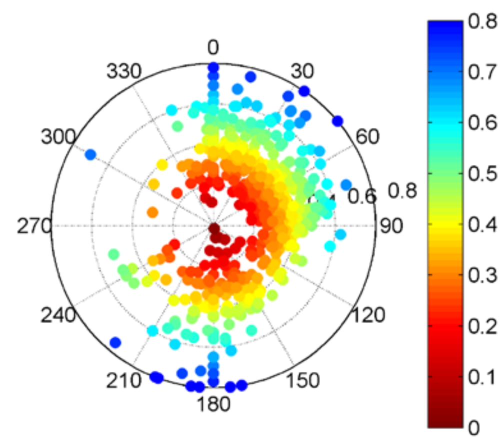

Figure 3: Distribution of modeled critical crack length r_c by aspect (degrees from North) for all field measurements hot colors indicating short cut lengths (N=613).

Snow depth

Snow depth was in one case (13 February 2012) negatively related to the critical crack length, i.e. the larger the snow depth the shorter the critical crack length (Table 2).

Considering all five field campaigns at the same field site deep snowpacks showed a significantly lower propensity for crack propagation (Table 2, Figure 4). The correlation was fair (r=0.2), but the linear trend was significant (p<0.01).

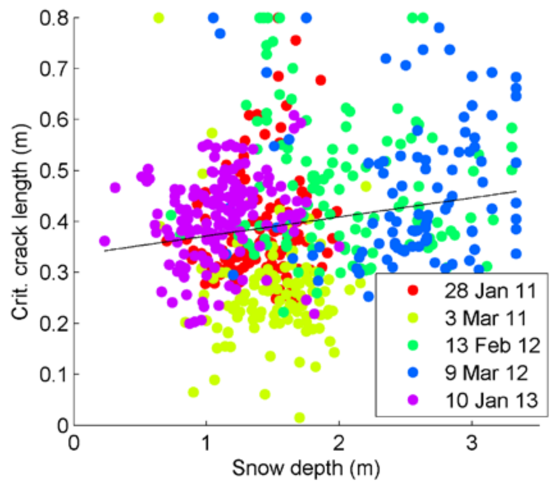

Figure 4: Modeled critical crack length vs snow depth with colors denoting different field days (see Table 1) and black line showing linear regression.

On one hand, thicker slabs release more energy and usually have shorter crack lengths given the same weak layer. On the other hand, weak layers below thick slabs are stronger, i.e. have higher specific fracture energy resulting in longer critical crack lengths. If we compare the same weak layer with slabs of different thickness above, we will rather observe the first case. Looking at a variety of slab and weak layer combinations, we will rather observe the second case with thick slabs yielding longer crack lengths. Thus, it comes with little surprise that the trends we find are not the same for the large dataset containing situations of much different snowpack layering and subsamples thereof containing variations of basically one stratigraphy.

Also in two cases snow depth was positively related to the stability criterion meaning the thicker the snowpack the harder failure initiation (Table 2). In contrast, the relation between snow depth and the failure initiation criterion was not significant for the entire dataset (Table 2).

Especially in view of crack propagation our findings indicate that the relation between snow depth and snow instability is not unambiguous. Regarding the entire dataset the general trend of lower values of our measures of snow instability in shallow snowpacks was present – even if not significant for the criterion *S*. Similarly, a significant positive correlation between snow depth and snow stability was frequently reported for different observation times and field sites with varying snowpacks on the regional scale (Schweizer et al., 2003; Zeidler and Jamieson, 2004).

Slope angle

In five out of the six cases where slope angle was a driver of snow instability steeper slopes had higher values of critical crack length and stability criterion *S* (Table 2). In the other four cases differences in our measures of instability were not related to slope angle. The positive correlation in five cases is in contrast with the concept of the skier stability index where the shear stress increases with increasing slope angle resulting in low values of the skier stability index. However, the distribution of steep slopes (> 30°) within our field site is imbalanced towards considerably more members on southern aspects. Thus, results for single days are questionable.

If all field days were considered the slope angle was not related to our measures of snow instability.

Studies investigating the role of the slope angle as a potential driver of snow instability found controversial results. Previous studies on the crack propagation propensity (Simenhois et al., 2012) and on snow instability in general (Schweizer et al., 2003) did not reveal a relation with slope angle. Jamieson (1999) and Campbell and Jamieson (2007), however, found a correlation of compression and rutschblock test results with slope angle, respectively. Our result for the entire dataset fits to the first group of studies suggesting no relation of slope angle with snow instability.

4. CONCLUSIONS

In this study, we presented a method to derive point stability estimates from SMP measurements. The presented method allows for objective snow instability measurements independent of the observer. By performing multiple spatially distributed measurements in an alpine basin, we investigated if snow stability patterns were related to simple drivers, such as snow depth, slope angle or aspect. Our results compared well with previous findings on the slope and the regional scale. Aspect and snow depth correlated with snow instability. The type of the relationship, positive or negative, between snow depth and crack propagation propensity, however, may vary for the type of weak and slab layer combinations under consideration. Slope angle was not a reliable indicator.

The results of this work may help to deepen our understanding of spatial variations of snow instability which may be helpful for avalanche danger assessment. Furthermore, the results are valuable for snow instability estimations, where direct information of snow instability is lacking between point observations, e.g. when applying forecasting models in data sparse areas.

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